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Towards the implementation of sustainable biofuel production systems

Diego F. Correa[a,b,*], Hawthorne L. Beyer[b], Joseph E. Fargione[c], Jason D. Hill[d], Hugh P. Possingham[b,e], Skye R. Thomas-Hall[a], Peer M. Schenk[a]

[a] Algae Biotechnology Laboratory, School of Agriculture and Food Sciences, The University of Queensland, Brisbane, QLD 4072, Australia
[b] Centre for Biodiversity and Conservation Science (CBCS), The University of Queensland, Brisbane, QLD 4072, Australia
[c] The Nature Conservancy, Minneapolis, MN 55415, USA
[d] Department of Bioproducts and Biosystems Engineering, The University of Minnesota, St. Paul, MN 55108, USA
[e] The Nature Conservancy, Arlington, VA 22203, USA

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ABSTRACT

Novel energy production systems are needed that not only offer reductions in greenhouse gas emissions but also cause fewer overall environmental impacts. How to identify and implement more sustainable biofuel production alternatives, and how to overcome economic challenges for their implementation, is a matter of debate. In this study, the environmental impacts of alternative approaches to biofuel production (i.e., first, second, and third generation biofuels), with a focus on biodiversity and ecosystem services, were contrasted to develop a set of criteria for guiding the identification of sustainable biofuel production alternatives (i.e., those that maximize socioeconomic and environmental benefits), as well as strategies for decreasing the economic barriers that prevent the implementation of more sustainable biofuel production systems. The identification and implementation of sustainable biofuel production alternatives should be based on rigorous assessments that integrate socioeconomic and environmental objectives at local, regional, and global scales. Further development of environmental indicators, standardized environmental assessments, multi-objective case studies, and globally integrated assessments, along with improved estimations of biofuel production at fine spatial scales, can enhance the identification of more sustainable biofuel production systems. In the short term, several governmental mandates and incentives, along with the development of financial and market-based mechanisms and applied research partnerships, can accelerate the implementation of more sustainable biofuel production alternatives. The set of criteria and strategies developed here can guide decision making towards the identification and adoption of sustainable biofuel production systems.

1. Introduction

Boosting economic growth while halting environmental degradation remains one of the major global challenges for humankind [1]. Current unsustainable use of the Earth's finite natural capital [2] has led to a wide range of negative impacts on the environment [3], including increasing biodiversity losses [4], alterations in the provision and quality of ecosystem services [5], and climate change [6]. These impacts and the decisions that society makes to reduce them, which include balancing human population growth [7] and planning for solutions based on multiple interacting environmental pressures [8], will have profound implications for global socioeconomic and environmental systems.

How to meet increasing energy consumption demands, while reversing environmental degradation, is a matter of debate [9]. Currently, the provision of energy relies primarily on fossil fuels, with around 5.8 $\times$ 10^{11} GJ consumed globally in 2016, of which 81% was derived from coal, petroleum, and natural gas [10]. Their associated greenhouse gas (GHG) emissions are linked to global warming and its negative impacts on biodiversity [11] and ecosystem services [12]. Limiting global warming to well below 2 °C compared to pre-industrial levels, a goal ratified by 185 parties (i.e., on February 2019) following the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in Paris [13], is expected to require the rapid adoption of renewable energy systems for replacing fossil fuels [14]. Consequently, the share of energy from renewable sources could increase from 9% of total primary energy demands in 2016 to 29% by 2040 [10].

While solar, wind and water as renewable energy sources could provide electricity with lower environmental costs compared to fossil fuels [15], liquid fuels are expected to remain necessary in the transport

* Corresponding author at: Centre for Biodiversity and Conservation Science (CBCS), The University of Queensland, Brisbane, QLD 4072, Australia.
E-mail address: diegofelipecorrea@gmail.com (D.F. Correa).

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Box 1
Biofuels, main production regions, and overlapping areas of high ecological importance.

Biofuel production involves the transformation of organic compounds—including cellulose, hemicellulose, lignin, starch, saccharose, and oils—from living organisms into carbon-rich carriers (e.g., alcohols and esters) that can be used for energy generation [29]. These organic compounds can come from a wide range of feedstocks (i.e., the range of sources from which biofuels are produced), including herbaceous and woody plants, oilseeds, agricultural and forestry wastes, and algae [30]. Feedstocks are transformed into biofuels through various combinations of thermochemical, biochemical, chemical and physical processes depending on feedstock properties (e.g., moisture content, proportions of fixed carbon and volatile matter, and cellulose/lignin ratios) [31]. Different environmental impacts, including habitat loss for native species [19], GHG emissions [20], emission of pollutants [21], and water withdrawals [32], arise from combinations of feedstock cultivation systems and their processing technologies.

According to REN21 [34], 133 × 10^9 L of liquid biofuels were produced in 2015, mainly in the forms of bioethanol (98.3 × 10^9 L, contributing to 74% of global biofuel production) and biodiesel (30.1 × 10^9 L, contributing to 23% of global biofuel production). Bioethanol production was led by the USA (57% of the total global bioethanol production), followed by Brazil (29%) and the EU-28 (4%), mostly from maize in the USA, maize and wheat in the EU-28, and sugarcane in Brazil. Biodiesel production was led by the EU-28 (38% of the global total production), followed by the USA (16%) and Brazil (14%) [34], primarily from rapeseed in Europe, and soybean in the USA and Brazil. Another widely used biodiesel feedstock is oil palm [35]. Cultivation of these crops overlaps with areas of high ecological importance, and have widely replaced native ecosystems, including native grasslands in the USA [36] and Brazil [37], as well as tropical and subtropical forests in South America [38] and Southeast Asia [39].

sector—mainly for aviation, shipping, and long-haul trucking—in spite of an expected increase in electric vehicles [16]. In fact, some scenarios for limiting global warming to 2 °C foresee biofuel production increasing from 9.7 × 10^6 GJ d^{-1} to 4.6 × 10^7 GJ d^{-1} between 2016 and 2040, reaching 16% of total transport fuels [10], though it remains unclear to what degree biofuel adoption would reduce net GHG emissions compared to other climate change mitigation options [17].

Current biofuel production is based on food crops (i.e., first generation biofuels) that compete with agricultural lands and biodiverse landscapes (Box 1, Fig. 1). Furthermore, biofuel production has been linked to several other environmental pressures that may, directly and indirectly, impact biodiversity and the provision of ecosystem services. These pressures [18] include direct and indirect land-use change [19], GHG emissions [20], emission of pollutants (i.e., from pesticides, fertilizers, biofuel production, and final use of biofuels) [21], water depletion [22], soil degradation and erosion [23], and introduction of invasive species [24]. The impacts of biofuels on biodiversity and ecosystem services, however, depend on the type of biofuel production system and several factors associated with its cultivation and production [19], including: the competing land-use and the spatial configurations of biofuel cultivation landscapes [25], their cultivation and conversion technologies [21], their cultivation management practices [26], their invasiveness potential [27], and the presence of co-products (Box 2) [28].

How to identify and implement more sustainable biofuel production alternatives [51], and how to overcome economic obstacles to their implementation, are unresolved challenges [52]. Here, the environmental impacts of several biofuel production alternatives (i.e., first, second, and third generation biofuels) on biodiversity and ecosystem services are evaluated. This information is integrated with criteria and avenues of research for guiding the identification and implementation of sustainable biofuel production alternatives (i.e., those that maximize socioeconomic and environmental benefits). Finally, promising strategies for overcoming economic barriers to adopt more sustainable biofuel production systems are discussed.

2. An overview of the environmental impacts of several biofuel production alternatives

First generation biofuels, which compete with agricultural and biodiverse lands, have led to habitat loss for native species [53] and associated GHG emissions [20] (Box 3). This mainly occurs by the direct replacement of biodiverse and carbon-rich original systems (i.e., direct land-use change) [19], and by the agricultural expansion outside biofuel production areas [43] as a consequence of increases in food prices generated by the competition with food production (i.e., indirect land-use change) [54]. For instance, between 1990 and 2005 in Southeast Asia, more than 55% of oil palm crops—which is used for human consumption and as a source for biodiesel production—came from oil palm plantations on converted native forests, directly increasing the extinction risk of thousands of species [55], while emitting large amounts of CO_2 into the atmosphere [20]. In Borneo, Sumatra and Peninsular Malaysia alone, it is estimated that the conversion of 6% of peat-swamp forests into oil palm by the early 2000s led to direct emissions of more than 140 Mt of CO_2 into the atmosphere plus ongoing annual carbon losses of around 4.6 Mt as a result of peat oxidation [56]. Conversion of peat-swamps and associated releases of CO_2 are ongoing [57]. The expansion of first generation biofuels has also impacted South America, where soybean cultivation—used for food, animal feed, and biodiesel production—has directly replaced large areas of the biodiverse Cerrado savannas [37], and indirectly driven deforestation in the Amazon forest for cattle production [38]. In North America, bioethanol production from maize has, directly and indirectly, promoted the replacement of native and planted grasslands [58]. Further cultivation of food crops for biofuel production threatens many other biodiverse and carbon-rich systems, including the African savannas [59] and several other suitable agricultural areas mainly in the highly productive tropical regions [60], as well as in developing economies with high energy demands (e.g., China) [61].

GHGs—including CO_2, methane (CH_4), nitrous oxide (N_2O), and carbon monoxide (CO)—as well as air pollutants—including ammonia (NH_3), volatile organic compounds (VOC), particulate matter (PM), nitrogen oxides (NO_x), and sulfur oxides (SO_x) [62]—are emitted during the replacement of original systems [63], cultivation and processing of feedstocks [64], transportation of biofuels to fuel stations, and final use of biofuels [49]. For instance, the emission of N_2O during the cultivation of crops with high nitrogen demands can offset CO_2 savings, as its global warming potential is 296 times larger than an equal mass of CO_2 [65]. Air pollution not only contributes to climate change, but also, directly and indirectly, impact species, ecosystems, and humans (e.g., through poisoning, acid rain, ozone layer depletion, tropospheric ozone formation, and changes in regional weather patterns) [66]. In fact, Tessum et al. [67] show that replacing conventional gasoline with corn ethanol in USA light-duty transportation can increase environmental health impacts by 80% from increased levels of O_3 and PM.

In the face of future agricultural expansion, alternatives that do not compete with food production or with biodiversity, and with fewer

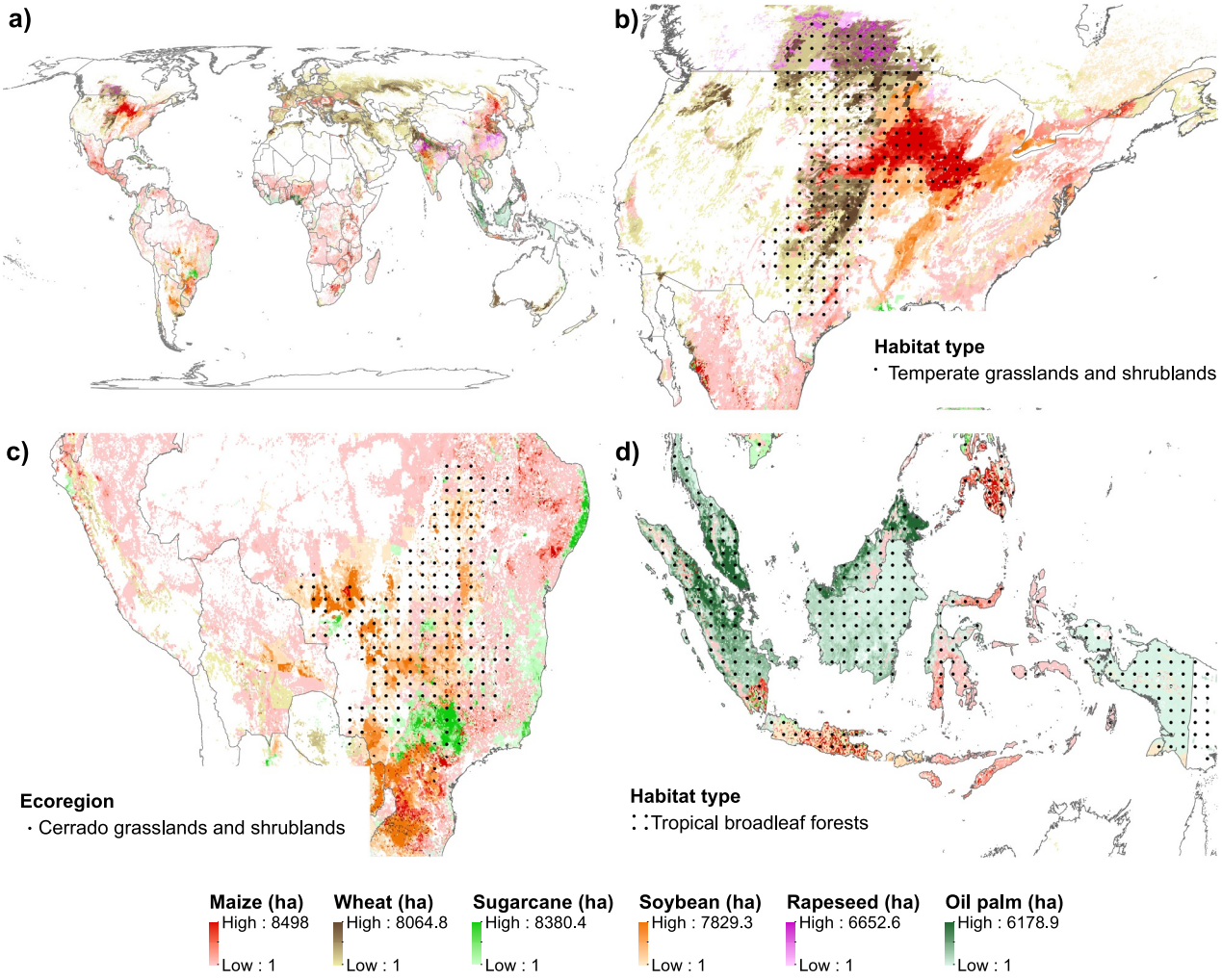

Fig. 1. Cultivation areas of food crops used for biofuel production globally (a) and overlapping habitat types and ecoregions (as dotted areas) [40] in North America (b), South America (c) and South East Asia (d). Total physical cultivation area for crops is based on the Spatial Production Allocation Model (SPAM) 2005 v.2.0 at 5′ grid cells [41].

direct and indirect impacts on biodiversity and ecosystem services, are needed to replace fossil fuels (Box 4, Fig. 2). Second generation biofuels, based on the transformation of the abundant lignin and cellulose found in non-food plants such as *Miscanthus* [71] and *Jatropha* [72,73], as well as in organic wastes [30], could lower competition with prime agricultural lands used for food production, as well as decrease the use of water, fertilizers, and pesticides [74]. The cultivation of second generation biofuels (e.g., willow, poplar, *Eucalyptus*, *Miscanthus,* and switchgrass) could, however, compete with important areas for biodiversity conservation [75], become invasive [24], drive soil water depletion in dry areas [76] (e.g., *Eucalyptus* plantations in Australia [77] and *Miscanthus* plantations in the Midwest USA) [78]) and emit considerable amounts of air pollutants including PM, NO_x, SO_x, NH_3, and VOCs [79]. Further negative impacts on key ecosystem services (e.g., water availability, disease and pest control, pollination, soil and water quality) would be expected when replacing forests and grasslands with second generation biofuels [80]. Additionally, indirect land-use changes would likely occur if demands for forest biomass increase, which would create incentives for further deforestation, particularly in tropical regions [81].

Intercropping biofuels in agricultural areas or timber plantations would also help in reducing competition with food production [33]. However, they could disturb native species that make use of the plantations depending on management practices [90] and, under some conditions, drive losses in soil carbon stocks. For instance, Strickland et al. [91] found that intercropping switchgrass within *Pinus taeda* plantations can reduce soil carbon during the first years following switchgrass planting.

While using wastes for biofuel production does not directly compete with agricultural or biodiverse lands, it could impact biodiversity and ecosystem services. For instance, the extraction of agricultural and forestry wastes can decrease soil carbon stocks and fertility in cultivation areas [92], negatively impact species that make use of decaying biomass [93], and indirectly drive deforestation as demand for biomass increases [81]. On the other hand, the use of plantations of native perennials on low-biodiversity or degraded lands could enhance the provision of several ecosystem services including carbon storage and pollination [94], as well as reduce the use of fertilizers and pesticides compared to conventional crops, allow the persistence of grassland or shrubland species, and reduce competition with food crops [33].

Third generation biofuels are mainly based on the use of microalgae (Box 5). This technology can be optimized to produce several types of biofuels, including biodiesel, bioethanol, biogas, and biohydrogen [95]. Because of high microalgal biomass productivities, microalgal systems require significantly less cultivation area to meet the same amount of energy compared to first and second generation biofuel crops (Table 1), particularly in areas with high solar radiation and high mean annual temperatures [18]. They do not require fertile soils, and so are not

Box 2
Factors that modify the environmental impacts of biofuel production.

The impacts of biofuel production on biodiversity and ecosystem services are modified by:

- Competing land-use: Determines how much GHG will be emitted [42] and how much biodiversity will be lost [19] after the replacement of original systems by biofuel production systems. The transformation of native ecosystems leads to fragmentation, habitat losses, and large CO_2 emissions arising from losses in biomass and soil carbon contents [28]. The competition with agricultural lands increases the potential for indirect land-use changes [43], leading to increases in CO_2 emissions, further biodiversity losses and environmental degradation outside biofuel cultivation areas [28].
- Spatial configurations of cultivation landscapes: Modifies the likelihood of species persistence at local and landscapes scales, as well as the provision of ecosystems services. For instance, a combination of intensive production areas, agroforestry systems, and forest patches (i.e., land-sparing) has been proposed as a way to maintain regional biodiversity and ecosystem services for oil palm cultivation [25]. Alternatively, biofuel cultivation areas could be managed to promote higher biodiversity (i.e., land-sharing) [44]. Jager and Kreig [45] propose the conservation of large patches of native ecosystems and the implementation of biological corridors at landscape scales (i.e., land-sparing), along with the reduction of production intensity at the scale of parcels (i.e., land-sharing).
- Biofuel cultivation and conversion technologies: Determines how much GHGs will be saved in comparison to fossil fuels, as a balance between inputs (e.g., fertilizers, energy used for converting feedstocks into biofuels) and products (i.e., biofuels and co-products) [21]. Affects water withdrawal [46] and the amount of emitted pollutants during the cultivation and processing of feedstocks [21], as well as the overall environmental impacts associated with biofuel production [18].
- Cultivation management practices: Modifies the magnitude of ongoing GHG emissions depending on how much fertilizer is used [21] and how soil is disturbed (e.g., frequent vs. sporadic soil tillage) [47]. For instance, Qin et al. [48] found that reducing tillage in USA maize-soybean production systems can offset GHG emissions derived from corn stover harvesting. Affects soil erosion rates, as well as pollution potential within and outside cultivation areas as a result of pesticide and fossil fuel use [18]. Impacts the persistence of native species within production areas [26].
- Invasiveness potential: Affects the local and regional persistence of native species, as well as the resilience of natural systems and their associated ecosystems services [24].
- Co-products: Affects the sustainability of biofuel production systems, as well as the emission of GHGs, pollutants, and energy efficiencies [21]. Can help in offset GHG emissions [49] and reduce external energy inputs dependent on fossil fuels [50].

expected to drive direct or indirect land-use changes within agricultural areas or biodiverse regions [96]. Several strains can be cultivated in brackish water or seawater [97], reducing competition with freshwater, and their dependence on environmental pollutants such as pesticides is lower compared to other terrestrial crops [98]. Furthermore, microalgal production systems can make use of residual CO_2 from industries (because supplementing algae production systems with CO_2 increases algal growth) and nutrients from wastewater, helping in carbon capture [99] and water remediation [100].

Although several potential environmental impacts of large-scale microalgal production systems remain unclear (e.g., carbon balances, nutrient use, invasiveness potential, pollution of aquatic ecosystems) [50], the development of more efficient cultivation and processing technologies that make use of renewable energy sources can improve the net GHG balances of microalgal production systems [101]. Furthermore, the recycling of culture media [102] and biomass residues (e.g., after lipids are extracted for biodiesel production), can reduce the use of freshwater [46] and fertilizers [69], while decreasing the risk of

Box 3
The controversial GHG emissions of biofuels.

In biofuel production systems, GHGs are emitted as a result of land-use changes [20], as well as during the cultivation of feedstocks [64], their harvesting, and their processing into biofuels (i.e., CO_2 emissions through soil disturbance, heterotrophic respiration, biomass combustion, and the use of energy-intensive processes) [68]. Further CO_2 emissions occur as a result of the production and transportation of inputs required for biofuel production (e.g., fertilizers), the transport of biofuels to fuel stations, and the final burning of biofuels for energy production [21]. Other GHGs, including CH_4, N_2O, and CO, are additionally emitted during the production and use of biofuels [62]. Currently, the accounting of GHGs derived from biofuel production as well as the definitive role of biofuel in climate change mitigation remain controversial [49]. However, in relation to CO_2 emissions, some consensus exists:

- To offset the CO_2 emitted by biofuel production, the carbon uptake during cultivation should be higher than the counterfactual reference system [42]. For instance, in Southeast Asia, it would take between 86 and 423 years to fix the CO_2 emitted when lowland rainforests and peatland rainforests are, respectively, transformed into oil palm plantations [20]. Even in systems with lower carbon stocks (e.g., grasslands), carbon emissions would be substantial. Searchinger et al. [59] estimate that in 99.4% of Africa's wet savannas more than 10 years would be needed to fix the CO_2 emitted following their replacement by second generation biofuels.
- CO_2 emissions can decrease through the use of carbon-efficient cultivation and conversion practices and technologies. This includes the use of systems with lower fertilizer use (e.g., soybean cultivation would need fewer fertilizers than maize) [21], the avoidance of detrimental soil management practices that drive carbon losses (e.g., reduced soil tillage) [47], and the optimization of energy-intensive processes for feedstock harvesting and conversion into biofuels (e.g., use of anaerobic digestion for nutrient recycling and energy production in microalgal production systems) [69].
- Carbon can be additionally captured and sequestered in long-term geological scales, for instance, using systems of bioenergy with carbon capture and storage (BECCS) [70].

Box 4
Future agricultural expansion, biofuels, and biodiversity.

Current species extinction rates are estimated at between 100 [4] and 1000 times greater [3] than those found in fossil records. For vertebrates, around 25% of mammal species, 13% of birds and 42% of amphibians are currently classified under some extinction threat category [82], and average losses in global population abundances are calculated at 58% between 1970 and 2012 [37]. Additionally, 20–50% of the original extent of nine of the 14 world's biomes has been transformed into croplands, with a notable loss of tropical dry forests, temperate grasslands, temperate broadleaf forests and Mediterranean forests [83]. As biodiversity continues to be negatively impacted by human activities—as a result of land-use change, fragmentation of native ecosystems, pollution, occurrence of invasive species, and climate change [83]—not only will more species risk extinction, but also ecosystem resilience will decrease, affecting the provision of multiple ecosystem services and ultimately the human wellbeing [84].

Increases in food and energy demands are expected to drive further pressures on biodiversity and ecosystem services, particularly when using biofuels derived from food crops [18]. Currently, around 34% of global terrestrial lands are used for agriculture, including 1.6×10^9 ha of rainfed and irrigated croplands, and 3.4×10^9 ha of pastures used for animal grazing [85]. At a population projection of around 9000 million people by 2050, it is expected that food demands will increase by more than 60% from 2006 levels [86], which could lead to an expansion of around 70 million ha for croplands, assuming that yields rise within current production systems [85]. This expansion is expected to occur mostly in tropical developing countries, placing additional pressures on tropical ecosystems [60].

Biofuel production systems that compete with agricultural lands are not only likely to threaten food production [87], but also are expected to magnify the environmental pressures and impacts on biodiversity and ecosystem services [88].

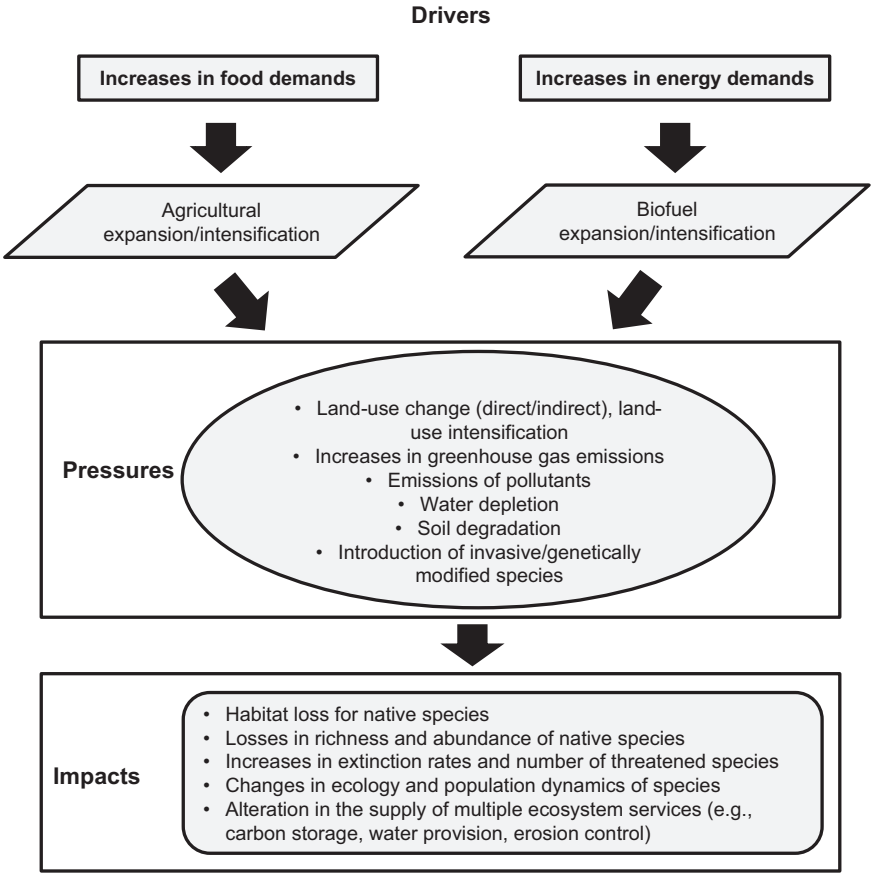
Drivers
Increases in food demands
Increases in energy demands
Agricultural expansion/intensification
Biofuel expansion/intensification
Pressures
• Land-use change (direct/indirect), land-use intensification
• Increases in greenhouse gas emissions
• Emissions of pollutants
• Water depletion
• Soil degradation
• Introduction of invasive/genetically modified species
Impacts
• Habitat loss for native species
• Losses in richness and abundance of native species
• Increases in extinction rates and number of threatened species
• Changes in ecology and population dynamics of species
• Alteration in the supply of multiple ecosystem services (e.g., carbon storage, water provision, erosion control)

Fig. 2. Magnification of pressures and impacts on biodiversity and ecosystem services exerted by the combined expansion of agriculture and first generation biofuels for meeting food and energy demands. Pressures are defined as anthropogenic factors that induce environmental impacts, based on the DPSIR framework [89].

polluting aquatic ecosystems [96], and the cultivation of microalgae with low invasiveness potential can avoid unintended ecological changes in surrounding aquatic environments [103].

3. Identifying and implementing sustainable biofuel production alternatives

If humankind is to halt further biodiversity losses and overall environmental degradation while limiting global warming [13], the identification and implementation of biofuel production systems must ensure that overall socioeconomic and environmental benefits are achieved (Fig. 3). Price competitiveness, affordability [114], and reliability in comparison to fossil fuels [115] are essential for the deployment of biofuel production systems. Systems that are able to meet biofuel production targets (i.e., based on their high production levels or the availability of feedstocks), as well as those able to meet socioeconomic targets [116] (e.g., welfare improvement in biofuel producing countries and local communities) [117] (Box 6), could be preferred

Box 5

Microalgal biofuel production: Higher productivities per unit area than other biofuel production crops.

Prokaryotic (i.e., cyanobacteria) and eukaryotic microalgae (e.g., green algae, red algae, and diatoms) can be cultivated for producing biogas, bioethanol, biodiesel, and biohydrogen [104]. Other products, including biochar, high-value compounds for human consumption, as well as fertilizer or animal feed can also be produced from microalgae [105].

Algae growth requires CO_2, light, and a growing medium with inorganic salts (i.e., water with nutrients such as nitrogen, phosphorus, iron, and silicon) [106]. Maximum productivities are achieved at high light intensities and constant high temperatures (usually between 20 and 30 °C) [106], and at a pH optimal to each microalgal strain [95]. Biomass productivities increase when supplemented with CO_2 [107], and when growth conditions are optimized to control algal grazers [108] and enhance biomass and lipid productivities [109].

Microalgae are among the most productive photosynthetic organisms on Earth [106]. Estimates on lipid productivities range from 2100 L ha^{-1} y^{-1} when cultivating *Spirogyra* sp. in urban wastewater ponds in India [110] to 136,900 L ha^{-1} y^{-1} if growing species with high oil content in photobioreactors [106]. According to Lundquist et al. [111] in theoretical optimal conditions biomass yields could reach 290 t ha^{-1} y^{-1} within the continental USA (i.e., oil yields equal to 126,000 L ha^{-1} y^{-1}), assuming conversion efficiencies of 10% from solar energy into biomass, high annual irradiances (i.e., at 7500 MJ m^{-2} y^{-1} in Yuma, Arizona) and cell lipid contents at around 40%. More conservative maximum oil yields are estimated at between 24,000 and 27,000 L ha^{-1} y^{-1}, which could be achieved within tropical countries with high solar irradiance [112]. For instance, when cultivating *Scenedesmus dimorphus* under subtropical conditions (Brisbane, Australia) it is possible to produce 72 t ha^{-1} y^{-1} of dry biomass, equivalent to around 19,400 L ha^{-1} y^{-1} (based on cell lipid contents at around 25% and oil densities at 930 kg m^{-3}) [113]. This means that the land footprint of microalgal production systems would be substantially lower compared to any other biofuel production system, including first generation biofuels [18].

over others. Furthermore, biofuel production systems with lower environmental impacts [118], or even environmental benefits, could contribute to achieve targets in carbon emission reductions, biodiversity conservation, and provision of ecosystem services [33]. These systems would need to provide large net GHG savings (including the avoidance of depleting existing carbon stocks in biomass and soil) [119], avoid competition with agricultural lands [33], avoid direct or indirect land-use changes in biodiverse areas [18], have low water footprints [120], and minimize pollution [21], soil degradation [121], and invasiveness potential [122]. Systems that maintain biodiversity and ecosystem services in the broader landscape (i.e., within and outside plantations) [25] could reduce regional biodiversity losses [123] while maintaining ecosystems services [94].

To facilitate the identification of sustainable biofuel production systems, a number of key knowledge gaps should be addressed:

(i) Development and standardization of indicators [132] for assessing the socioeconomic and environmental impacts of biofuel production alternatives. For biofuels, multiple indicators have been proposed in relation to soil and water quality, GHGs, air quality, and productivity [133], as well as in relation to social well-being, energy security, trade, profitability, and social acceptability [134]. However, a more comprehensive development of some indicators, including those related to biodiversity and ecosystem services

Table 1

Cultivation area (thousand km^2) for fulfilling total transport energy demands for biggest energy consuming countries in 2016 (i.e., countries that account for 80% of world's total transport energy consumption), based on first (1 G), second (2 G), and third generation (3 G) biofuels. The percentage of cultivation area (%) in relation to each country's land area is included. See Appendix A for details on calculations and Correa et al. [18] for comparisons with other countries.

Country	1G biofuels												2G biofuels						3G biofuels	
	Ethanol						Biodiesel						Ethanol				Biodiesel		Biodiesel	
	Wheat		Maize		Sugarcane		Soybean		Rapeseed		Oil palm		Switchgrass		*Miscanthus*		*Jatropha*		Microalgae	
	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%	Area	%
United States	10,094	106	2987	31	1922	20	14,119	149	11,014	116	–	–	3524	37	1153	12	4681	49	622	7
China	2905	31	2422	26	1009	11	11,515	122	4997	53	1242	13	1679	18	549	6	2229	24	353	4
Russia	2003	12	989	6	–	–	5000	30	2574	15	–	–	531	3	174	1	–	–	157	1
India	1483	47	1624	51	306	10	5707	180	2412	76	–	–	–	–	–	–	673	21	66	2
Brazil	1629	19	800	9	265	3	1934	23	2096	25	390	5	–	–	–	–	620	7	61	1
Japan	938	251	1308	350	308	82	3019	809	1609	431	–	–	408	109	133	36	–	–	83	22
Canada	948	10	294	3	–	–	1455	15	934	9	–	–	344	3	113	1	–	–	108	1
Germany	372	104	277	78	–	–	1811	508	496	139	–	–	322	90	105	30	–	–	89	25
Mexico	503	26	751	38	174	9	2370	121	1573	80	222	11	–	–	–	–	396	20	39	2
Indonesia	–	–	457	24	200	11	2228	117	–	–	155	8	–	–	–	–	353	19	36	2
Saudi Arabia	374	20	377	20	–	–	–	–	–	–	–	–	–	–	–	–	342	18	33	2
Iran	1256	77	309	19	135	8	1388	85	798	49	–	–	252	16	83	5	335	21	34	2
France	319	58	235	43	–	–	1102	201	416	76	–	–	248	45	81	15	–	–	52	10
United Kingdom	261	107	–	–	–	–	–	–	374	153	–	–	231	95	76	31	–	–	68	28
Italy	462	154	182	60	–	–	728	242	479	159	–	–	203	68	67	22	–	–	35	12
South Korea	546	544	343	341	–	–	1457	1450	1118	1113	–	–	199	199	65	65	–	–	43	43
Australia	824	11	232	3	97	1	1096	14	805	10	–	–	185	2	61	1	246	3	22	0
Spain	510	101	131	26	181	36	763	151	471	93	–	–	174	34	57	11	–	–	27	5
Turkey	498	64	150	19	–	–	451	58	246	32	–	–	150	19	49	6	–	–	25	3
Thailand	1246	241	280	54	83	16	1104	213	–	–	76	15	–	–	–	–	188	36	21	4
Malaysia	–	–	149	45	163	49	–	–	–	–	64	19	–	–	–	–	161	49	17	5
South Africa	281	23	192	16	69	6	766	63	443	36	–	–	–	–	–	–	141	11	14	1
Egypt	146	15	117	12	39	4	399	40	–	–	–	–	105	11	34	3	140	14	13	1

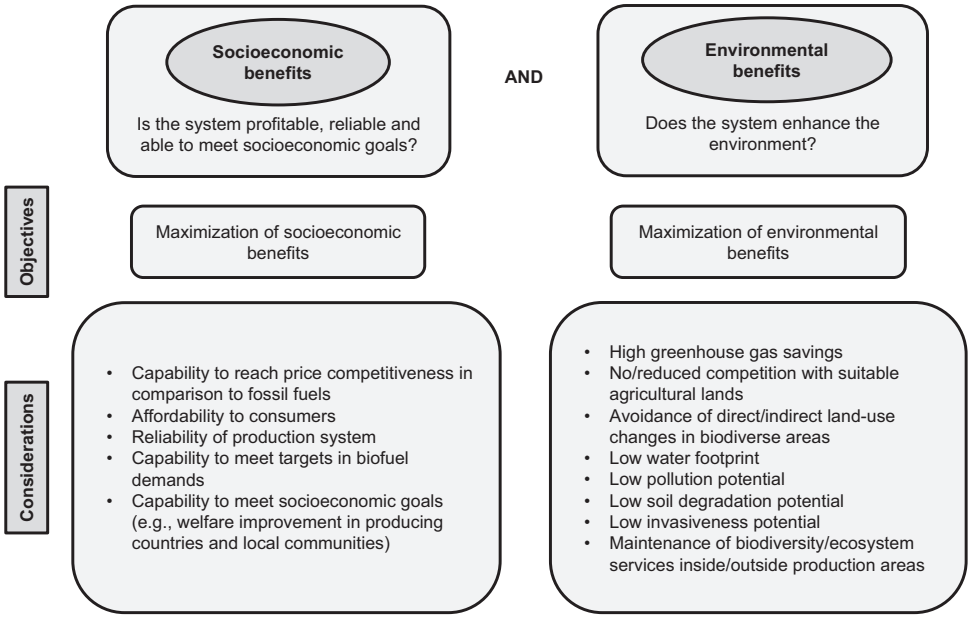
Socioeconomic benefits
Is the system profitable, reliable and able to meet socioeconomic goals?
AND
Environmental benefits
Does the system enhance the environment?
Objectives
Maximization of socioeconomic benefits
Maximization of environmental benefits
Considerations
Capability to reach price competitiveness in comparison to fossil fuels
Affordability to consumers
Reliability of production system
Capability to meet targets in biofuel demands
Capability to meet socioeconomic goals (e.g., welfare improvement in producing countries and local communities)
High greenhouse gas savings
No/reduced competition with suitable agricultural lands
Avoidance of direct/indirect land-use changes in biodiverse areas
Low water footprint
Low pollution potential
Low soil degradation potential
Low invasiveness potential
Maintenance of biodiversity/ecosystem services inside/outside production areas

Fig. 3. Criteria to be considered when evaluating the socioeconomic and environmental benefits of biofuel production systems.

[135,136], would improve the understanding of the overall environmental impacts of biofuel production, and facilitate the assessment of biofuel production sustainability [137]. The standardization of indicators, which simplifies their selection and use, would benefit from the participation of stakeholders (i.e., academy, government, industries, non-governmental organizations, and communities) [138] and the understanding of the causal relationships between indicators and biophysical, socioeconomic, and governance drivers [139].

(ii) Development of standardized assessments on the environmental impacts exerted by biofuel production systems. This includes the development of life-cycle assessments (LCA) that make use of the same system boundaries (e.g., well-to-wheel studies that consider cultivation, biofuel production, and final use of biofuels by consumers), impact categories, and functional units [140]. These standardized assessments would facilitate objective and measurable comparisons between different studies, as well as the development of meta-analysis on the environmental impacts of several biofuel production alternatives [141]. For instance, Harris et al. [142] report that there are insufficient empirical assessments to determine the impacts of second generation biofuels on GHG emissions; while Tu et al. [143] indicate the need to harmonize assumptions, data sources, and calculation procedures in LCA, for the development of meta-analyses able to draw valid conclusions on the overall environmental impacts of microalgal production systems.

(iii) Development of case studies that consider multiple socioeconomic and environmental objectives (e.g., taking into account targets in energy and food production, biodiversity conservation, and provision of multiple ecosystem services) in several locations. Techniques for identifying multiple objective solutions include multi-criteria decision analysis (MCDA) [144], multi-agent systems (MASs) [145], and integer linear programming [146]. These studies require the participation of stakeholders for defining objectives, environmental indicators, criteria [147], and their weights (e.g., through analytical hierarchy process AHP) [148]. Furthermore, they would help to identify the synergies and trade-offs among objectives and criteria, for instance, between land and water requirements [149], between biodiversity and climate change mitigation [150], or among deforestation, CO_2 emissions, nitrogen losses, water withdrawals, and food prices [151]. The robustness and uncertainty of models and results can be assessed through the development of sensitivity analyses [152]. To date, several frameworks have been developed to facilitate the inclusion

Box 6

The social impacts of first generation biofuels.

Biofuel production has been linked to a wide range of negative socioeconomic impacts, closely related to those exerted by large-scale farming systems. Controversies exist on the actual benefits of agricultural and biofuel expansion in developing countries, where rural poverty and informal land tenure are prevalent [124]. While the production of biofuels can bring economic incentives to developing nations and help in poverty alleviation through the creation of jobs [125], it can negatively impact land rights [81], drive rises in land prices, as well as alienate, marginalize, and displace locals [126]. Biofuels have additionally been related to increases in food prices [54], directly affecting smallholder farmers and urban dwellers in developing economies [127] that depend on external agricultural markets for surviving [128].

However, it has been proposed that several of the impacts attributed to biofuel production rely on the weak governance of developing nations to protect small landholders [117]. Several governance mechanisms—including policies that promote the diversification of land production while preventing deforestation [129], or the implementation of certification schemes aimed at increasing social welfare in local communities [130]—can help to reduce the reported negative socioeconomic impacts of biofuel production in the developing world [131]. In the face of future increased energy and food demands, the use of non-food crops for biofuel production would be expected to reduce these impacts.

Box 7
Microalgal cultivation systems (open ponds and photobioreactors).

Microalgal cultivation systems include open ponds, photobioreactors, and fermenters [170]. Raceway ponds are the most widely used type of open ponds and consist on a closed recirculation channel, built in concrete or with plastic covering the earth, usually with a depth between 15 and 30 cm, in which algae and growth medium are mixed by paddlewheels [95]. Microalgae concentrations are low, CO_2 can be added to the water for maximal productivity, and the temperature is not controlled although evaporation helps to cool the medium [106]. Compared to photobioreactors, this system experiences higher water losses through evaporation, is less efficient in CO_2 uptake, and is more prone to contamination by other microorganisms, which results in reduced yields [105], but is considered a more cost-effective option for biofuel production [50].

Photobioreactors can consist of a series of plates, tubes, bags, columns or domes set in particular arrangements that maximize sunlight uptake. Algae concentrations are usually higher than in open ponds, the light intensity can be better optimized, the temperature can be controlled, though energy or water use increase, and CO_2 can be injected at several intervals in order to ensure continuous carbon uptake, leading to higher biomass yields than those obtained in open ponds [95]. However, setup costs may be ten times higher than those necessary for the construction of open ponds [95], and hence are considered less cost-effective to date [50].

Hybrid systems are based on the initial growth of microalgae in photobioreactors, avoiding contamination from other microorganisms, followed by their cultivation in open ponds [171] (Fig. 4).

of multiple objectives in biofuel decision making. For instance, Zhang et al. [153] developed a multi-objective and spatially explicit framework for biofuel production in Michigan, based on GIS, biomass yields, and trade-offs among biofuels and ecosystem services; Perimenis et al. [154] developed a support tool for helping decision makers in selecting more sustainable biofuel production alternatives in Germany; and Garcia and You [155] developed a framework to select the most sustainable bioethanol production alternative based on global life-cycle environmental impacts (i.e., land-use change and GHG emissions) and production costs. Expanding on this work by developing detailed case studies that consider a broad range of objectives and impacts would establish an evidence-base for informing policy and planning decisions.

(iv) Improved estimation of potential biofuel production at fine spatial scales, accounting for a wide range of factors that can impact both feasibility and yield [156]. Biofuel production is limited by the availability of lands for the cultivation of feedstocks [157], and the availability of the several resources involved in their production, including freshwater [158] and nutrients (e.g., nitrogen and phosphorus) [159]. For instance, potential global bioenergy production from wastes, including agricultural and forestry residues, would be lower compared to energy crops (i.e., 25–221 EJ y^{-1} vs. 22–1272 EJ y^{-1}) [157] and may be further constrained after taking into account environmental considerations for maintaining soil fertility, carbon stocks and biodiversity associated with decaying biomass [75]. The understanding of these limits and uncertainties can help decision makers choose biofuel production alternatives able to meet substantial amounts of fuel demands.

(v) Development of standardized and integrated global assessments of the impacts of biofuel production considering complex socio-economic and ecological systems (e.g., integrated assessment modeling IAM) [88]. These assessments would facilitate the understanding of the complex actual and potential impacts of biofuel production alternatives at multiple spatial and temporal scales. For instance, based on the Shared Socio-Economic Pathways (SSEPs) Popp et al. [70] suggest that high levels of bioenergy production modeled on second generation biofuels can be achieved with low impacts on ecosystems, if future demand for agricultural commodities remains low, if agricultural productivity increases, and if globalized trade is maintained.

4. Economic profitability: a current barrier to the deployment of more sustainable biofuel production systems

Economic profitability is the main barrier to the deployment of more sustainable biofuel production systems. Currently, the lowest biofuel production costs are achieved by first generation biofuels, particularly for sugarcane bioethanol in Brazil and maize bioethanol in the USA, helped in part by government subsidies [160]. High costs for converting lignocellulosic feedstocks into biofuels [160] and high capital and operational costs for setting up microalgal production systems [161], reduce the economic competitiveness of lignocellulosic and microalgal biofuel production systems. While production costs for sugarcane in Brazil and maize in the USA have been calculated at between US$ 5–9 and US$ 9–20 GJ^{-1}, respectively, estimated production costs for lignocellulosic feedstocks and microalgal systems (i.e., often based on assumptions about production technologies and production costs) can range between US$ 19–62 and US$ 13–8949 GJ^{-1}, respectively [160]. For comparison, an oil price of US$ 100 $barrel^{-1}$—a price which has only been exceeded in 20% of months in the past decade [162]—is equivalent to US$ 17.12 GJ^{-1} (Low Heat Value LHV). To be competitive, more sustainable biofuel production alternatives must approach cost equivalence with its competitors.

The cost-effectiveness of more sustainable biofuel production alternatives is expected to benefit from increased scale efficiencies and learning rates as biofuel production farms enlarge and production technologies evolve. Historical trends show significant cost reductions that several biofuel production systems—including bioethanol production from sugarcane in Brazil and from maize in the USA—have experienced as the industry matured, which is also expected to occur for more sustainable biofuel production alternatives [163]. For second generation biofuels, the development of more cost-effective conversion technologies based on the transformation of lignocellulosic feedstocks is needed [164]. For microalgal production, the cultivation of highly productive microalgal strains [106] and the co-location with inexpensive CO_2 and nutrient sources (i.e., co-locating microalgal cultivation systems with CO_2 from industries and nutrients from wastewater) improve the profitability of microalgal production systems [165], particularly for open ponds (Box 7) [50]. Reductions in production costs between 35% and 86% can be achieved if CO_2 from industries and nutrients from wastewater are obtained for free [165]. Additionally, more efficient cultivation methods (e.g., using less energy-intensive mixing techniques for promoting microalgal growth) [166], along with low-cost harvesting and de-watering methods [50] and the development of profitable co-products (e.g., animal feed and biogas) [167], can increase both the profitability and sustainability of microalgal biofuel production [168]. For instance, the defatted residues that remain after lipids are extracted for biodiesel production can be used as a substrate for biogas generation and for nutrient recycling (i.e., following anaerobic digestion) [69]; this biogas can either be sold or used as a source of energy and CO_2 for algae cultivation, reducing energy costs and increasing microalgal growth, while nutrient recycling

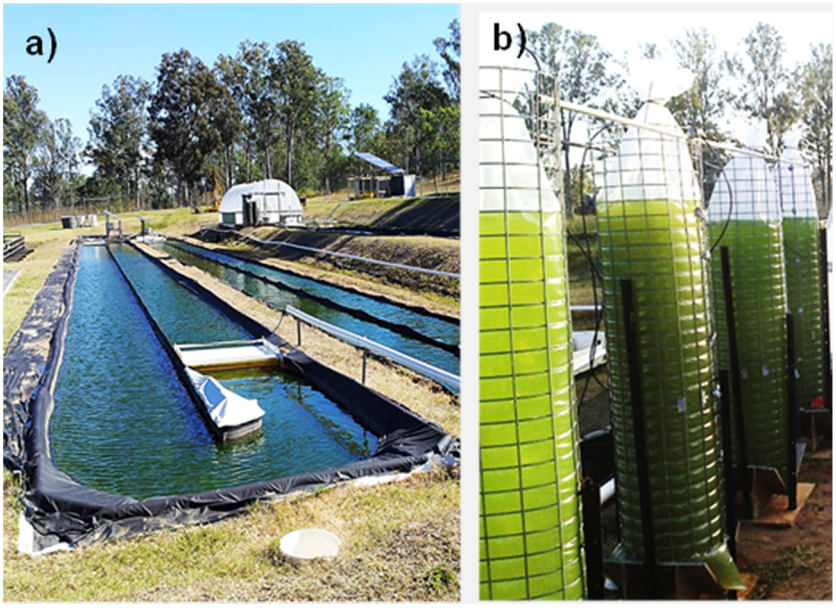

Fig. 4. UQ Algae Energy Farm at Pinjarra Hills, Brisbane, Australia (Algae Biotechnology Laboratory, University of Queensland). Cultivation is based on open ponds (a) following initial growth in sealed bags and a series of smaller ponds (b).

reduces the dependence on fertilizers [169].

Several strategies can facilitate the transition of transport systems based on fossil fuels and first generation biofuels to systems based on sustainable biofuels and electricity (Fig. 5) [172]. In the short term, the development and commercialization of high-value products can provide profits and enable scaling of production. For lignocellulosic biomass, a biorefinery system, in which value-added products such as bio-oil, biochar, and other bio-based chemicals can be produced, is expected to increase the profitability of second generation biofuels [173]. Similarly, for microalgal production systems, a biorefinery-based production model [174], in which different types of biofuels are produced (e.g., biogas and biodiesel) [69] or high-value products for food consumption and animal feed (e.g., omega-3 fatty acids, pigments, proteins, and fishmeal) are produced along with biofuels [161], can increase the profitability of microalgal biofuel production.

Several policies can be implemented to promote the deployment of more sustainable biofuel production systems, as has already occurred for first generation biofuels in the USA, Brazil, Europe, and other economies [175]. They include:

(i) The introduction of biofuel blending mandates that require sustainable biofuel production methods, following a comprehensive evaluation of their socioeconomic and environmental benefits [176]. For instance, by 2020 the European Union aims to meet 10% of total transport energy demands using renewables based on the use of biofuels that do not drive direct or indirect land-use changes in biodiverse and carbon-rich regions, and that additionally deliver GHG savings of at least 35% in comparison to fossil fuels (and from 2018, of at least 60%), considering the cultivation, processing, and transport of biofuels [177]. The development of these mandates should consider synergies and trade-offs among biofuel production, socioeconomic, and environmental goals; for instance, among biofuel cultivation, restoration of degraded lands [178], ecosystem services [179], and biodiversity conservation [180].

(ii) The taxation or subsidizing of energy systems based on their environmental impacts. This would include the elimination of fossil fuel subsidies, the implementation of disincentives to less sustainable biofuels (e.g., through carbon taxation schemes) [181]

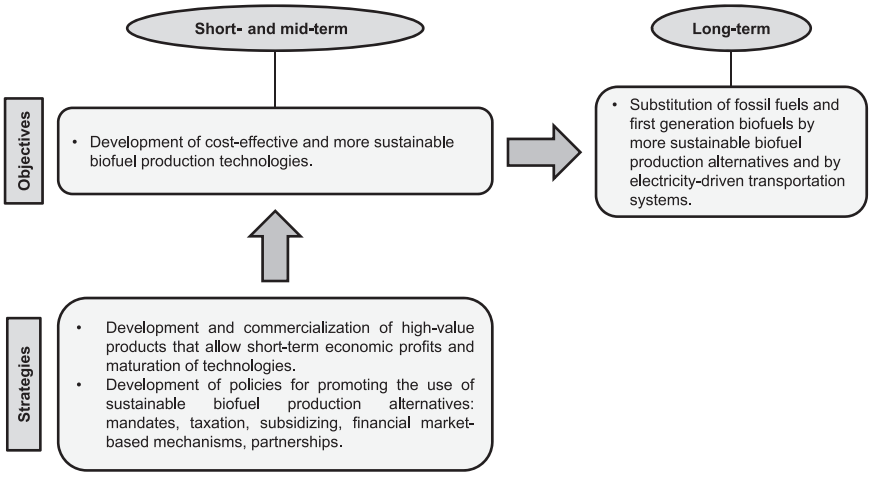
Short- and mid-term
Long-term
Objectives
• Development of cost-effective and more sustainable biofuel production technologies.
• Substitution of fossil fuels and first generation biofuels by more sustainable biofuel production alternatives and by electricity-driven transportation systems.
Strategies
• Development and commercialization of high-value products that allow short-term economic profits and maturation of technologies.
• Development of policies for promoting the use of sustainable biofuel production alternatives: mandates, taxation, subsidizing, financial market-based mechanisms, partnerships.

Fig. 5. Strategies for promoting the implementation of more sustainable biofuel production alternatives in the short and long term.

and the subsidizing of more sustainable biofuel production alternatives while the subsidies for first generation biofuels gradually decrease [182]. This can boost the deployment of promising more sustainable biofuel production systems while they become economically competitive [183].

(iii) The implementation of financial and market-based mechanisms for promoting the development of sustainable biofuel production alternatives. For instance, the use of contracts for difference (CFDs), in which biofuel producers enter a 10-year contract with governments following reverse auctions, has been proposed as a more cost-effective alternative for financing the setup of ultralow-carbon biofuels in California in comparison to capital grants [184]. Other mechanisms include the integration of novel and more sustainable biofuel production systems with carbon markets [185] and sustainability certifications schemes [130], which can increase their profitability based on environmental advantages (e.g., reductions in GHG emissions) compared to less sustainable energy production alternatives.

(iv) The development and strengthening of partnerships between governments, universities, and industries, for promoting research and innovation aimed at developing more profitable and sustainable biofuel production alternatives [186].

5. Articulation of policies at the global, national, and regional level

The transition to a more sustainable transport sector can be fostered through the development of strategic policies that promote the adoption of sustainable biofuel production alternatives that are able to reduce environmental impacts and halt competition with food production [187]. The articulation of policies at global, regional, national, and local scales is a necessary step for guiding the implementation of sustainable biofuels (Fig. 6). The development of an updated global roadmap on sustainable biofuels [188] could guide nations in implementing policies in accordance with global multi-objective targets while balancing local socioeconomic and environmental needs [189]. Because the impacts of biofuel systems are still a matter of debate, this roadmap must be subject to adjustments as new evidence on the impacts of biofuels is established (i.e., through the development of an adaptive framework on the global and local socioeconomic and environmental impacts of biofuels) [190]. At the global scale, the biofuel industry can be supported through the development of international standards to facilitate accreditation of fuel sustainability [130], markets to support international trade of sustainable biofuels [191], and trade agreements to ensure that pricing of sustainable biofuels remains competitive [192]. Furthermore, the development of international agreements based on sustainability goals (e.g., the Paris Agreement, to which most countries are signatories) provides strong incentive and justification for fostering the growth of more sustainable biofuel production systems.

National energy policy is fundamental to drive the transition to sustainable biofuels [193]. National mandates on biofuel blends based on stringent biofuel sustainability standards [194] can encourage the implementation of sustainable biofuels. The gradual replacement of fossil fuels and first generation biofuels can be facilitated through: (i) National-level policies that provide disincentives to fossil fuel and unsustainable biofuel production (e.g., through carbon taxation schemes) [181] and (ii) national-level incentive programs that promote sustainable biofuels, including the subsidizing of sustainable biofuel production, the development of financial and market-based mechanisms mediated by governments in favor of sustainable biofuels [184], and the funding of applied research to develop cost-effective and sustainable biofuels [195].

Regional level policy is critical to ensure that the growth of the biofuel industry occurs in a strategic way, avoiding biodiversity impacts, competition for agricultural land, non-sustainable use of resources (e.g., freshwater), and negative socioeconomic impacts [189]. Regional policy can also manage trade-offs among multiple stakeholders and potential conflicts among industries [196], as well as help to regulate the growth of biofuels and certificate sustainable biofuels [130].

6. Conclusions

Bioenergy production is expected to increase from 9.7×10^6 to 4.6×10^7 GJ d^{-1} between 2016 and 2040 [10], and how biofuels are produced will determine their overall environmental impacts. The implementation of more sustainable biofuel production systems, which currently include sustainably sourced wastes, native perennial crop, and microalgal production systems produced on low-biodiversity or

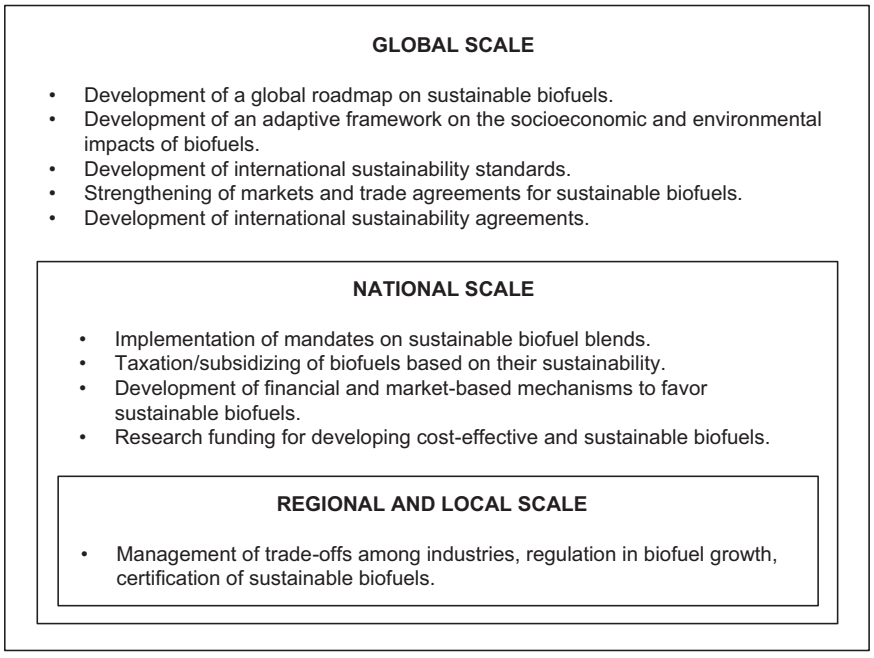
GLOBAL SCALE
• Development of a global roadmap on sustainable biofuels.
• Development of an adaptive framework on the socioeconomic and environmental impacts of biofuels.
• Development of international sustainability standards.
• Strengthening of markets and trade agreements for sustainable biofuels.
• Development of international sustainability agreements.
NATIONAL SCALE
• Implementation of mandates on sustainable biofuel blends.
• Taxation/subsidizing of biofuels based on their sustainability.
• Development of financial and market-based mechanisms to favor sustainable biofuels.
• Research funding for developing cost-effective and sustainable biofuels.
REGIONAL AND LOCAL SCALE
• Management of trade-offs among industries, regulation in biofuel growth, certification of sustainable biofuels.

Fig. 6. Articulation of policies at the global, national, regional, and local scale towards the implementation of sustainable biofuels.

degraded lands, could reduce the magnitude of the several socio-economic and environmental impacts exerted by first generation biofuels, mainly in terms of reduced competition with food production and biodiversity. The sustainability of these and other novel biofuel production alternatives must be carefully assessed before their widespread adoption, based on global socioeconomic and environmental targets (e.g., poverty reduction, climate change mitigation, biodiversity conservation, freshwater provision, and reduction of eutrophication). The development of robust assessments that consider the social and environmental impacts of biofuel production are needed to inform choices and implement more sustainable biofuel production alternatives. This could involve, for example, the development and standardization of environmental indicators, the development of standardized assessments on the environmental impacts exerted by biofuel production systems, the development of detailed case studies that consider multiple socio-economic and environmental objectives, improved estimations of potential biofuel production feasibility and yield, and the development of integrated assessments to understand the socioeconomic and ecological implications of biofuel production alternatives. Technological improvements are expected to improve the profitability of more sustainable biofuel production alternatives over time, currently estimated at between US$ 19–62 for lignocellulosic feedstocks and US$ 13–8949 GJ^{-1} for microalgal production systems [160]. Meanwhile, several policies (i.e., mandates, taxation, subsidizing, financial and market-based mechanisms, and applied research partnerships) can foster the development and adoption of more sustainable biofuel production systems. These policies should be articulated at the global, national, and regional levels. Third generation biofuels are a key technology for meeting long-term transport energy demands while reducing land-use changes. For instance, in Russia, India, Brazil, Canada, Mexico, Indonesia, Saudi Arabia, Iran, Australia, South Africa, and Egypt, microalgal cultivation would require less than 2% of each country's land area for fulfilling their current domestic transport energy demands.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2019.03.005.

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